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Modeling and Exploiting of Dense Plasma Foci as Compact Accelerators

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White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing “P” in right column.

Indicate secondary area or areas by placing “S” in right column

	“P”, “S”
• Plasma Atomic physics and the interface with chemistry and biology	S
• Turbulence and transport	S
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• Plasma self-organization	S
• Statistical mechanics of plasmas	P

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Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Modeling and Exploiting of Dense Plasma Foci as Compact Accelerators
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(Limit text to 3-pages including this form. Font Times Roman size 11.

1 page of references and 1 page of figures may also be included. Submit in PDF format.)

• ***Describe the research frontier and importance of the scientific challenge.***

The dense plasma focus (DPF) is a type of plasma gun that ends in a z-pinch phase. It relies on the implosion of a gas discharge sheath to generate dense plasmas energetic electron and ion beams along the axis of the device. [1] The device is triggered using a pulsed power driver such as a capacitor bank to generate breakdown across an insulator and to push the plasma sheath down the length of the gun. These devices take advantage of inherent instabilities as the plasma reaches peak current density so that the plasma produces an intense, short pulse of both radiation and accelerated (100keV – 10MeV) ions and electrons within a small volume. If deuterium is used in the device, the accelerated deuterium collides with deuterium ions within the pinch, as well as background deuterium gas, generating short pulses of neutrons. [2] These devices do not require advanced pulse compression technology that typically characterizes traditional z-pinches, and are, most importantly, scalable to different desired beam intensities.

Modeling pinch behavior requires an understanding of each phase of operation of the DPF. DPF devices generally take the form of two coaxial cylindrical conductors, an inner anode and an outer cathode, extending from a base plate, as shown in Fig. 1. When a high voltage is placed across these conductors gas between the conductors begins to ionize along the back plate, forming a conduction path.

The resulting plasma sheath travels up the conduction tube due to $\mathbf{j} \times \mathbf{B}$ forces on the sheath. Once the sheath reaches the end of the anode, it is drawn in radially towards the pinch location on the axis of the device. Instabilities, driven by a large change in plasma impedance at this point, lead to large fluctuations in the field, and therefore fast transient accelerating potentials.

While DPFs have been around for many years, we have only recently gained the ability to accurately simulate them due to the recent advances in kinetic particle-in-cell modeling. In the past, attempts to model the physics of DPF devices at the pinch location relied on an MHD approach which does not self-consistently include kinetic effects such as anomalous plasma resistivity/viscosity and beam formation. Kinetic effects are critical [3] both to understand the distribution of accelerated particles and to understand in detail that physical processes that lead to this acceleration. Our group has developed a fully kinetic model of a DPF pinch in the large-scale plasma (LSP) particle-in-cell (PIC) code[4] which captures these important phenomena. Examples of this are shown in Fig. 2. This fully kinetic model has been shown to reproduce experimentally observed neutron yields, ion beam energies, and instabilities for the first time. [5]

• ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Each of the stages of the DPF operation requires accurate physical models of the plasma sheath behavior to properly predict behavior in subsequent phases. This includes a wide range of physics for accurate modeling, including accurate atomic physics, plasma physics, and surface-interface models to understand the dynamics of gas discharges in the system. Many of these models, in particular the interaction of the plasma with the electrode material, do not exist or are incomplete; this is an issue our group is working to address. In general, these simulations are extremely computationally intensive since it requires resolving picosecond processes evolving over a microsecond timescale in the device.

Pinch performances in certain regimes can be unpredictable, and beam yields can be highly variable under identical experimental conditions. One of the major challenges in DPF physics will be developing an understanding of which instabilities lead to desirable pinch behavior and finding methods to preferentially seed these instabilities in the plasma sheath during the “run-down” and “run-in” stages of operation. We are currently investigating the use of supersonic gas jets to seed density perturbations for this purpose.

These simulations have been benchmarked on DPF’s operating over a wide range scales from 100J to 1MJ [6], shown in Fig. 3. [7] It is an open question how the physics scales amongst these devices, and we hope to demonstrate that similar acceleration dynamics can be achieved over this wide range of device specifications. An example of a known issue in scaling is the observation that pinch performance is typically heavily degraded when the current driven in the plasma exceeds 3MA in large devices.[8] On the other hand, certain parameters such as the driver impedance (as shown by the SPEED experiments in Fig. 3) [9] have been shown to dramatically increase performance for otherwise similar devices. Understanding and then taking advantage of the physics behind these observations is major goal of our group.

Benchmarking to current devices is absolutely critical for demonstrating validity of the code at these different scales. This requires a suite of diagnostic systems for existing high-current DPF experiments with a focus on acquiring information useful to benchmark the simulation behavior. These diagnostics include:

- Current monitoring on the anode and cathode of the device
- Optical imaging of the pinch using fast-frame cameras
- Direct x-ray imaging of the pinch region
- Optical/UV/X-ray Spectrometers for temperature measurement and contamination monitoring
- Pulsed laser interferometers for density measurement

- Residual gas analysis systems for pressure and gas-mix monitoring
- Ion spectrometers for beam characterization
- Neutron detectors for deuterium and tritium devices

While many smaller DPF's contain some number of these diagnostics, it will be necessary to develop additional instruments to get better quality data on all currently-operating devices and thus better constrain the simulations.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

DPF devices may have a variety of direct and indirect benefits for plasma science. The devices themselves can be used as compact particle accelerators and neutron sources. Using predictive models, DPF's could eventually be engineered as reliable radiation generating devices for a variety of other systems. In addition, the non-MHD regimes that we hope to address in simulations may prove useful for other physical systems that are generally difficult to simulate.

As compact accelerator platforms, DPF's can be used as a safer alternative to material radioactive sources. The ions accelerated by the DPF can be tuned to have similar energy distributions to common radioactive sources and can effectively replace intense alpha sources in many applications. Since the DPF is able to use non-radiological materials, such as helium gas, to generate these ions, there is significantly reduced environmental and safety hazard in operating these devices. As an accelerator, the DPF can be used to generate on-demand neutrons from D-D collisions. This can be particularly useful for portable neutron imaging, radiological material detection, and material analysis platforms or other applications that may require short, intense pulsed neutron sources.

Along the way, we hope that techniques developed for simulations advance general understanding and modeling of plasma physics in non-fluid regimes. Turbulent astrophysical plasmas can exhibit anomalous resistive behavior similar to pinch behavior, and the simulation techniques developed for DPF's might be applicable to these systems. [10] Surface effects may play a significant role in the behavior of the sheath, and detailed modeling of these effects may prove useful for other gas-discharge systems.

Large-scale DPF pinches can serve as excellent experimental platforms for studying high energy density plasmas (HEDP) due to the high-velocity implosion of the plasma sheath. They operate at a high-repetition rate (~40 shots/day) compared to experiments that reach similar energy densities.

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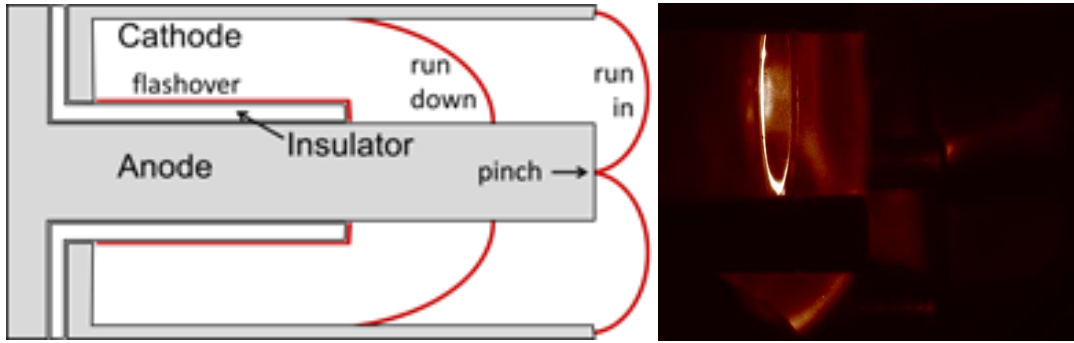


Figure 1: Cartoon cross-section schematic of a DPF. Initially, the gas between electrodes is ionized along the insulator at the base of the tube. The sheath runs down the length of the tube, runs in radially once it reaches the end and finally pinches on axis. A photograph of the LLNL 2kJ pinch during the “run in” phase, looking radially inwards at the tip of the anode, is shown on the right.

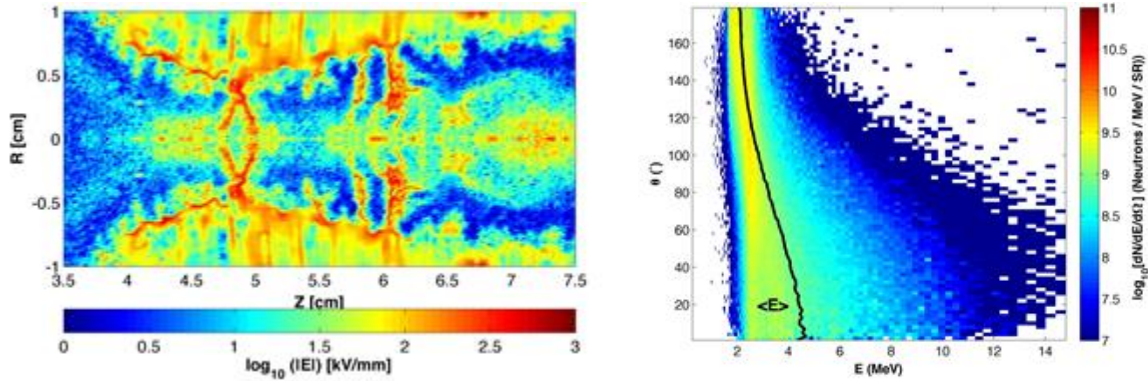


Figure 2: Simulation results for a MJ-scale deuterium DPF performance. In the pinch region (*left*), large electric fields generated by instabilities are observable in high fidelity kinetic simulations. From these results a neutron yield distribution, as a function of emission angle from the machine axis, (*right*) from subsequent D-D collisions in the plasma can be predicted to high resolution.

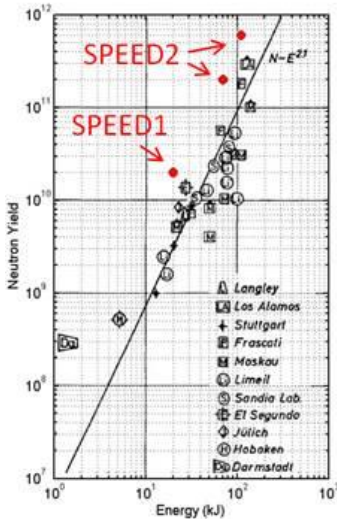


Figure 3: Scaling of performance (in this case, by neutron yield) as a function of the energy stored in the pulsed power drivers for various DPF experiments. The SPEED DPF devices have performed significantly better than most experiments by relying on high impedance drivers and different anode geometry, a feature we hope to capture through simulations and implement in future devices.